MARINE QUICK CLAYS FROM ARIAKE BAY AREA, JAPAN

MASAMI OHTSUBO*, MASATERU TAKAYAMA** and KAZUHIKO EGASHIRA***

ABSTRACT

It has been indicated that the sensitivity of the marine sediment in Ariake Bay area varies between 8 and 50, and rarely is 100. Recently, however, extra quick clays with sensitivity greater than 50 and sometimes near 1000 were found in this area. In order to find the cause of the formation of extra quick clays, the sediment samples of slightly-very quick and extra quick clay obtained from two sites in Ariake Bay area were analyzed with respect to their mineralogical, chemical, and geotechnical properties. There was no appreciable difference in clay mineralogy between the sediment samples from two sites, and they contained smectite as the main mineral. The principal difference between the sediment samples of slightly-very quick and extra quick clay was in the salt concentration in the pore water, which was in the range of 1.02~10.4 g/l and 0.05~1.08 g/l, respectively.

The experiments of salt addition to extra quick clays and salt leaching from medium quick clays demonstrated that extra quick clays could be developed by leaching out of the salt in the pore water. The fact that extra quick clays can be developed in the sediment in Ariake Bay area, in spite of the presence of smectite as the main mineral, was interpreted by considering smectite in the clays to be of low-swelling type.

Key words: alluvial deposit, clay mineral, cohesive soil, leaching, physico-chemical properties, sensitivity, soft ground (IGC : D2)

INTRODUCTION

The clayey sediment 15 to 42 m thick is widely distributed in Ariake Bay area of Kyushu, Japan. Ariake Bay Research Group (1965) investigated the fossil assemblages of the sediment, and suggested that the upper clay layers above a depth of 10-11 m and lower clay layers below 10-11 m were deposited under near marine and brackish conditions, respectively. The sediment consists mainly of smectite accompanied by vermiculite, illite, and kaolinite (Aomine et al., 1954; Kobayashi and Oinuma, 1964). Geotechnical investigations of the sediment (Fujikawa and Takayama, 1980) indicated that the sensitivity of the sediment varies between 8 and 50, and rarely is 100. Taka-

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yama (1975) demonstrated from the laboratory tests on thixotropic hardening for remoulded samples that thixotropic hardening can account for the sensitivity below fifty of natural Ariake marine sediment. Recently, however, the extra quick clays with the sensitivity greater than 50 and sometimes near 1000 were found in Ariake Bay area. Since such extremely high sensitivity of the sediment cannot be explained solely by thixotropic hardening, additional reasons for the sensitivity development should be considered.

The marine quick clays with the sensitivity of 8-1000 are extensively developed in Scandinavia and Canada, and leaching out of the salt in the pore water has been indicated as a predominant cause of their high sensitivity by many authors. Rosenqvist (1953) first proposed that salt leaching was responsible for the development of the marine quick clays. Skempton and Northey (1952), and Bjerrum and Rosenqvist (1956) showed from the leaching experiments on Norwegian clays that their liquid limit and undisturbed and remoulded shear strength decreased as the salt content in the pore water decreased. Bjerrum (1954), based on data from the natural quick clay deposits, revealed that their peculiar geotechnical properties are mainly a result of reduced salt concentration in the pore water. These reports suggest a possibility that the extra quick clays in Ariake Bay area have been developed by leaching out of the salt in the pore water.

The quick clays in Scandinavia consist predominantly of non-swelling minerals like quartz, feldspar, illite, and chlorite (Berry and Jørgesen, 1971). Mineralogically the formation of the quick clays in Scandinavia is owing to the predominance of non-swelling minerals (Torrance, 1975). Therefore, the mineralogical composition of the extra quick clays in Ariake Bay area has to be examined.

In this study, the chemical, geotechnical, and mineralogical properties of the samples of quick clay sediment obtained from two sites in Ariake Bay area are examined. Then, the experiments of salt addition and salt removal are made to examine whether extra quick clays can be developed by leaching out of the salt in the pore water.

**MATERIALS AND METHODS**

**Materials**

The sampling sites are shown in Fig. 1. The samples used in this study were obtained as tube samples at three sites, Yamaashi, Higashi-shiroishi, and Ariake-kantaku (Shiroishi-cho, Kishima-gun, Saga Prefecture). The sediment at the Higashi-shiroishi and Ariake-kantaku sites, and the Yamaashi site have the sensitivity in the range of 14-41 and 18-836, respectively. The Yamaashi and Higashi-shiroishi sites are located at a distance of 50 m from the Rokkaku River, and about 9 km and 6 km from the sea shore, respectively. The altitude of the sites is 0.9 m and 2.2 m, respectively. The Ariake-kantaku site is located at a distance of 2 km from the sea shore and its altitude is 0 m.

**Methods**

Chlorid ion concentration: One g of air-dried samples was taken and 50 ml of 1 M NaNO₃ were added. The suspensions were shaken for 1 hour followed by centrifugation and filtration. The concentration of Cl⁻ in
the extract was measured using an ion meter. The salt concentration in the pore water was calculated as NaCl from Cl⁻ concentration.

Water-soluble cation concentration: One g of air-dried samples was taken and 50 ml of water was added. The suspensions were shaken for 1 hour followed by centrifugation and filtration. The concentrations of Na⁺, K⁺, Ca²⁺ and Mg²⁺ in the extract were measured using an atomic absorption spectroscopy.

Cation exchange capacity (CEC): Ca (CH₃COO)₂ method by saturating with Ca and extracting with Na.

pH: 1 : 2.5 soil–water suspensions were used for the measurement.

Clay mineral composition: Clay fractions (<2 μm) were separated from the mud samples and their mineralogical composition was determined by an X-ray diffraction method using CuKα radiation (Wada, 1966).

Specific surface area: The surface areas of Na-saturated clays freeze-dried from dispersed clay suspensions were measured with ethylene glycol monoethyl ether (Egashira et al., 1977).

Shear strength: The undisturbed shear strength of the samples was determined by the unconfined compression test. The remolded strength of the clay samples is so low that the vane shear test was used for its measurement. The ratio of peak undisturbed strength (c=σ_u/2) to remoulded strength (c_r) was used as sensitivity.

### CHEMICAL, GEOTECHNICAL, AND MINERALOGICAL PROPERTIES OF SEDIMENT

The chemical and geotechnical properties of the sediment at the Higashi-shiroishi and Yamaashi sites are shown in Figs. 2 and 3, respectively. The natural water content is greater than the liquid limit in all the Higashi-shiroishi and Yamaashi samples, but the liquidity index in the latter is higher than that in the former. The unconfined compressive strength increases linearly with depth, and the increase rate of strength with depth changes at a depth of 10—11 m for both samples. The sensitivity of the Higashi-shiroishi samples is less than 50, and this extent of sensitivity has been found commonly for the sediment in Ariake Bay area (Fujikawa and Takayama, 1980). The sensitivity of the Yamaashi samples is lower.

![Fig. 2. Chemical and geotechnical properties of Higashi-shiroishi clay profile](image-url)
Fig. 3. Chemical and geotechnical properties of Yamaashi clay profile

Fig. 4(a). X-ray diffraction patterns of the Mg-saturated and glycerol-solvated specimen of <2 μm clay fractions

Fig. 4(b). X-ray diffraction patterns of the K-saturated and air-dried specimen of <2 μm clay fractions
than 100 at the depths of above 10 m, but remarkably increases with depth below 10 m. Most of the samples from the Yamaashi site are classified as extra quick clays (Rosengvist, 1958).

The concentration of Cl⁻ of the Higashi-shiroishi samples increases to a depth of 5 m and then decreases with further depth. A similar change in Cl⁻ concentration was found in the sediment right after reclamation or in the sediment below sea level (Yamaguchi and Oka, 1960; Fujikawa et al., 1978). The Yamaashi samples show a similar pattern in Cl⁻ concentration variation to the Higashi-shiroishi samples, but the concentration for the former samples are less than one tenth of those for the latter samples. The total concentration of water-soluble cations exceeds Cl⁻ concentration for both Higashi-shiroishi and Yamaashi samples, and this difference is greater for the Yamaashi samples. The water-soluble cation in the pore water of the Yamaashi samples prepared by pressing field-moist samples also presented a similar pattern in their variation to that in Fig.3. Such a discrepancy between the total concentrations of water-soluble cations and Cl⁻ concentration may be a result of the extraction of a portion of exchangeable cations.

Fig. 4 shows the X-ray diffraction patterns of the <2μm clay fractions of the samples from different depths. The X-ray diffraction patterns reveal that smectite is the principal mineral accompanied by kaolinite, illite, and vermiculite for all the samples. Table 1 gives the specific surface areas of the <2μm clay fractions, and most of them is above 400 m²/g. Egashira (1981) reported that soil clays containing smectite as the predominant mineral had a specific surface area of above 400 m²/g. These results of surface area measurement and X-ray diffraction indicate that the clay fractions of both Higashi-shiroishi and Yamaashi samples contain smectite as the main mineral and there is no appreciable difference between them in their clay mineralogy.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (m)</th>
<th>Specific surface area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higashi-shiroishi</td>
<td>3.3</td>
<td>461</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>433</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>437</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>423</td>
</tr>
<tr>
<td></td>
<td>13.6</td>
<td>402</td>
</tr>
<tr>
<td></td>
<td>15.2</td>
<td>396</td>
</tr>
<tr>
<td>Yamaashi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1. Specific surface areas of the <2μm clay fractions of Higashi-shiroishi and Yamaashi samples**

**Fig. 5. Relationships between the shear strength of undisturbed and remoulded clays and water content**

**EFFECT OF SALT CONCENTRATION ON SENSITIVITY**

The relationships between the shear strength of undisturbed and remoulded clays and their water content are shown in Fig.5. The shear strength decreases with increasing water content for the undisturbed samples, but it is lower and varies in a wide range at a given water content for the remoulded samples. These results suggest that the remoulded shear strength is not solely controlled by the water content. Skempton and Northey (1952), and Houston and Mitchell
(1969) indicated that the remoulded shear strength of a clay depends on the liquidity index: defined by the expression \( I_L = (\omega - \omega_p)/(\omega_L - \omega_p) \), where \( \omega \), \( \omega_L \), and \( \omega_p \) denote the water content, liquid limit, and plastic limit, respectively. When the water content equals the liquid limit, \( I_L = 1.0 \), and when the water content equals the plastic limit, \( I_L = 0 \). For the Higashi-shiroishi and Yamaashi samples, the remoulded shear strength correlates with the liquidity index (Fig.6).

The liquidity index may be expected to be correlated with the salt concentration for the Higashi-shiroishi and Yamaashi samples, because the liquid limit is a function of the salt concentration in the pore water for Ariake marine clays (Ohtsubo, 1982). Fig.7 shows that such a correlation exists. That the remoulded shear strength is a function of the liquidity index, and the liquidity index is a function of the salt concentration in the pore water is reflected on the relationship in Fig.8 where the remoulded shear strength increases with increasing salt concentration. The sensitivity \( (\Rightarrow c/c_L) \) is correlated with the salt concentration in the...
pore water (Fig.9), because the remoulded shear strength is a function of the salt concentration (Fig.8).

**SALT ADDITION AND SALT REMOVAL**

The experiments of salt addition to extra quick clays and salt removal from medium quick clays were made to demonstrate that extra quick clays could be developed by leaching out of the salt in the pore water.

**Salt addition**

The experiments of salt addition were conducted to examine whether the shear strength of the remoulded samples from the Yamaashi site increases with increasing salt content. Salts were added to the remoulded samples from the depths of 6.5 m, 13.5 m, 15.5 m, and 16.5 m, and their liquid limit, plastic limit, and remoulded shear strength were determined. Assuming that the Yamaashi and Higashi-shiroishi samples originally retained the same amount of salt, the salt concentration in the pore water of the Yamaashi samples was adjusted to be almost equal to that of the Higashi-shiroishi samples of the corresponding depth. For the adjustment of salt contents, the salt solution having an ionic composition similar to the sea water was used. The weight proportions of the ions were Na : K : Mg : Ca = 84 : 3 : 10 : 3. The chemical and geotechnical properties before and after salt addition are shown in Table 2. All the samples exhibit increases in the liquid limit and remoulded shear strength, and a decrease in the liquidity index after addition of salt. These results suggest the possibility that the extremely high sensitivity at the Yamaashi site was developed by leach-

**Table 2. Chemical and geotechnical properties before and after addition of salt to remoulded Yamaashi samples**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Salt concentration in the pore water (g/l)</th>
<th>Water content (%)</th>
<th>Consistency limits (%)</th>
<th>Liquidity index</th>
<th>Shear strength (kN/m²)</th>
<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>Before addition of salt</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6.5</td>
<td>0.82</td>
<td>106</td>
<td>61</td>
<td>30</td>
<td>31</td>
<td>2.39</td>
</tr>
<tr>
<td>13.5</td>
<td>0.35</td>
<td>95</td>
<td>63</td>
<td>35</td>
<td>28</td>
<td>2.14</td>
</tr>
<tr>
<td>15.5</td>
<td>0.12</td>
<td>90</td>
<td>54</td>
<td>30</td>
<td>24</td>
<td>2.79</td>
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<tr>
<td>16.5</td>
<td>0.12</td>
<td>85</td>
<td>53</td>
<td>27</td>
<td>26</td>
<td>2.23</td>
</tr>
<tr>
<td>After addition of salt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>8.01</td>
<td>105</td>
<td>67</td>
<td>36</td>
<td>31</td>
<td>2.20</td>
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<td>13.5</td>
<td>4.39</td>
<td>95</td>
<td>75</td>
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<tr>
<td>15.5</td>
<td>3.10</td>
<td>96</td>
<td>74</td>
<td>33</td>
<td>41</td>
<td>1.52</td>
</tr>
<tr>
<td>16.5</td>
<td>1.58</td>
<td>85</td>
<td>73</td>
<td>34</td>
<td>39</td>
<td>1.31</td>
</tr>
</tbody>
</table>

**Table 3. Changes in chemical and geotechnical properties of undisturbed Ariake-kantaku samples by salt leaching**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Overburden pressure (kN/m²)</th>
<th>Depth (m)</th>
<th>Content of &lt;2μm clay fraction (%)</th>
<th>Amount of percolation water (l/m²)</th>
<th>Salt concentration in the pore water (g/l)</th>
<th>Water content (%)</th>
<th>Consistency limits (%)</th>
<th>Activity</th>
<th>Liquidity index</th>
<th>Shear strength (kN/m²)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-4</td>
<td>19.6</td>
<td>4.2~4.3</td>
<td>52.8</td>
<td>0</td>
<td>5.27</td>
<td>100</td>
<td>120</td>
<td>62</td>
<td>57</td>
<td>1.08</td>
<td>1.70</td>
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<td></td>
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<td></td>
<td></td>
<td>20</td>
<td>3.98</td>
<td>153</td>
<td>117</td>
<td>56</td>
<td>58</td>
<td>1.10</td>
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<td></td>
<td></td>
<td></td>
<td>40</td>
<td>2.75</td>
<td>172</td>
<td>110</td>
<td>49</td>
<td>61</td>
<td>1.15</td>
<td>2.03</td>
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<td></td>
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<td>60</td>
<td>1.23</td>
<td>169</td>
<td>103</td>
<td>56</td>
<td>47</td>
<td>0.89</td>
<td>2.43</td>
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<td></td>
<td></td>
<td></td>
<td>80</td>
<td>0.05</td>
<td>161</td>
<td>95</td>
<td>56</td>
<td>39</td>
<td>0.75</td>
<td>2.66</td>
</tr>
<tr>
<td>A-8</td>
<td>32.3</td>
<td>8.5~8.8</td>
<td>45.0</td>
<td>0</td>
<td>5.38</td>
<td>126</td>
<td>106</td>
<td>42</td>
<td>63</td>
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<td>1.34</td>
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<td>1.76</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>164</td>
<td>0.23</td>
<td>130</td>
<td>78</td>
<td>45</td>
<td>33</td>
<td>0.73</td>
<td>2.58</td>
</tr>
<tr>
<td>A-12</td>
<td>50.0</td>
<td>12.4~12.8</td>
<td>26.0</td>
<td>0</td>
<td>3.10</td>
<td>68</td>
<td>46</td>
<td>34</td>
<td>12</td>
<td>0.46</td>
<td>2.77</td>
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<td>0.94</td>
<td>62</td>
<td>43</td>
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<td>2.18</td>
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<td>0.58</td>
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<td>30</td>
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<td>0.36</td>
<td>3.02</td>
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<td>80</td>
<td>0.23</td>
<td>58</td>
<td>37</td>
<td>29</td>
<td>8</td>
<td>0.30</td>
<td>3.69</td>
</tr>
</tbody>
</table>
burden pressure of the respective samples was applied on the specimens. One of these specimens was stored without leaching, and the others were subjected to leaching by percolating distilled water under a water pressure of 0.5 kN/m². Different amounts of distilled water were percolated through each of the specimens for 3 to 60 hours. At the end of leaching the undisturbed and remoulded shear strength of the specimens in the oedometer rings was measured by the vane shear test. The water content, consistency limits, and salt concentration in the pore water of the specimens were also determined. In determining the liquid limit, the water content of the specimens was reduced to a value lower than the liquid limit by sucking pore water to prevent any change in the salt concentration in the pore water. The results are given in Table 3. In sample A-4, leaching caused a substantial reduction in the salt concentration in the pore water, and the liquidity index and sensitivity increases from 1.70 to 2.66 and 23 to 718, respectively. The increase in the liquidity index is accompanied by a decrease in the liquid limit without any significant reductions in the plastic limit and water content. The increase in sensitivity is entirely due to a reduction in the remoulded shear strength without any significant change in the undisturbed shear strength. Similar results were obtained for samples A-8 and A-12. These results demonstrate that extra quick clays can be formed by salt leaching.

**DISCUSSION**

The quick clays in Scandinavia consist mainly of non-swelling minerals like illite and chlorite, but the clay fractions of the quick clays in Ariake Bay area consist predominantly of smectite. Warkentin (1961) and Warkentin and Yong (1962) showed that Na-montmorillonite, because of its unrestricted swelling, exhibits increases in the liquid limit and remoulded shear strength with decreasing salt contents. Torrance (1975), by adding pure montmorillonite to a marine

**Salt removal**

The experiments of removing salt from undisturbed clay samples were made to demonstrate that medium quick clays can change to extra quick clays when they are subjected to leaching. The undisturbed marine clay samples collected from the Ariake-kantaku site were employed instead of the Higashi-shiroishi samples in the experiments. The clay samples from the Ariake-kantaku site did not differ appreciably from the Higashi-shiroishi samples in their sensitivity (Table 3) and clay mineralogy (Fig. 10). The specific surface areas of the <2 μm clay fractions of samples A-4, A-8 and A-12 were 437, 431 and 425 m²/g, respectively.

The specimens which were cut from an undisturbed sample were placed in oedometer rings, and the load equivalent to the over-
quick clay from Mastermyr, Norway, demonstrated that as little as 4% of this swelling mineral precluded the possibility of this soil exhibiting liquid behaviour upon remoulding. These reports suggest that Ariake marine sediment has lesser probability to develop to extra quick clays by salt leaching. However, the liquid limit and remoulded shear strength of the Yamaashi and Ariake-kantaku samples decreased by a reduction in salt contents despite the fact that these samples contain smectite as the main mineral, and extra quick clays were developed. Egashira and Ohtsubo (1981) found abnormal phenomena in the liquid limit of a recent marine mud from Ariake Bay which contains smectite as the main mineral: the liquid limit of the mud decreased as the salt content was lowered. To explain such phenomena they proposed the low-swelling smectite different from the normal, high-swelling smectite. Egashira and Ohtsubo (1982) indicated that the smectite in the Yamaashi and Ariake-kantaku samples is also of low-swelling type. Therefore, the decrease in the liquid limit and remoulded shear strength of the Yamaashi and Ariake-kantaku samples with decreasing salt contents can be explained due to the low-swelling characteristic of the smectite.

The following process can be proposed for the development of extremely high sensitivity at the Yamaashi site. The deposits at the Yamaashi site, which originally retained salt contents similar to those at the Higashishiroishi site, have been subjected to leaching due to the slow flow of ground water, resulting in a reduction in the salt concentration in the pore water to a quantity less than 1.0 g/l. The reduction in the salt concentration in the pore water lowered the liquid limit and remoulded shear strength, whereas the natural water content, plastic limit, and undisturbed shear strength were remained unchanged. Consequently, the liquidity index increased, and extremely high sensitivity was developed. The increases in the sensitivity and liquidity index due to a reduction in the salt concentration in the pore water are reflected on the sensitivity versus liquidity index relationship for the Higashishiroishi and Yamaashi samples (Fig. 11). The sensitivity is correlated well with the liquidity index for the Higashishiroishi and Yamaashi samples, as well as for Norwegian clays (Bjerrum, 1954).

CONCLUSIONS

Both the sediment of extra quick and slightly-very quick clays consist predominantly of smectite with minor quantities of vermiculite, illite, and kaolinite. On the other hand, the salt concentration in the pore water of the sediment of extra quick and slightly-very quick clays varied between 0.05 and 1.08 g/l, and between 1.02 and 10.40 g/l, respectively. The sensitivity of the quick clays was inversely correlated with the salt concentration in the pore water.

The experiments of salt addition to extra quick clays and salt leaching from medium quick clays demonstrated that extra quick clays could be developed by leaching out of the salt in the pore water. The extremely high sensitivity of the sediment which contains smectite as the main mineral was explained by a low-swelling characteristic of the smectite.
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